CANADA
DEPARTMENT OF ENERGY, MINES AND RESOURCES
OBSERVATORIES BRANCH

CONTRIBUTIONS
from the
Dominion Observatory
OTTAWA

No. 300

GRAVITY STUDIES OVER THREE EVAPORITE PIERCEMENT DOMES IN THE CANADIAN ARCTIC

BY

ALLAN SPECTOR AND ROBERT W. HORNAL

Reprinted for private circulation from
GEOPHYSICS
Vol. XXXV, No. 1, February, 1970

GEOPHYSICS, VOL. 35, NO. 1 (FEBRUARY 1970), P. 57–65, 7 FIGS., 1 TABLE

GRAVITY STUDIES OVER THREE EVAPORITE PIERCEMENT DOMES IN THE CANADIAN ARCTIC†

ALLAN SPECTOR* AND ROBERT W. HORNAL‡

Reconnaissance gravity surveys over three evaporite piercement domes in the Canadian Arctic Islands have been interpreted. Each dome was considered as a right-vertical cylinder divided into two homogeneous regions, a high density anhydrite zone (2.9 gm/cm^3) overlying a low density gypsum and/or rock salt zone (2.3 gm/cm^3). The cylinder is surrounded by a sedimentary sequence which has a uniform density of 2.4 gm/cm^3. Interpretation involved a least-sum-of-squares approach to estimate the thickness of the anhydrite and gypsum-rock salt zones. The three sets of estimates gave a range of 200 to 550 m for the anhydrite thickness and a range of 700 to 5500 m for the vertical extent of domes. In each case the depths were less than expected on the basis of estimates from seismic and geological data. Possible explanations for this are: (a) the cross-sectional area of each dome decreases with depth; (b) the existence of a transition zone where a gradation occurs between the high and low density zones; and (c) the effective density contrast of the low density zone is less than 0.1 gm/cm^3.

INTRODUCTION

The evaporite piercement structures of the Canadian Arctic Islands are among the most interesting physiographic and geological features of this northern region. The diapirs have been divided into three categories according to structure (Hoen, 1964): the large, roughly circular, domical diapirs or domes, which will be studied in this report; the more irregular, anticlinal diapirs; and the fault diapirs. The domes form prominent topographic features rising 100 to 400 m above the surrounding terrain and have a radius of 2.5 to 3.5 km. Unlike the more common salt domes studied in the Gulf Coast of the United States and elsewhere, the major constituents of the domes appear to be anhydrite and gypsum. Isolated blocks of limestone and inclusions of igneous rocks are also found. Aeromagnetic profiles across the domes reveal generally well-defined anomalies due in part to upturned igneous sills around the rims of each dome (Gregory et al, 1961).

In the early 1960's gravity surveys were made over three of the more prominent circular domes—the Cape Colquhoun Dome on Melville Island, the Isachsen Dome on Ellef Ringnes Island and the South Fiord Dome on Axel Heiberg Island (Figure 1). In this paper these gravity observations are used to estimate the vertical extent of the evaporite columns.

GEOLOGY

The geological setting of the piercement structures is shown in Figure 1. The diapirs are found along the axis of the Sverdrup Basin which is a great sediment-filled depression whose rocks, chiefly sandstone and shale, date from late Carboniferous to early Tertiary time. As much as 10 km of sediment accumulated in some places along the 600 km-long axis of the basin. Beneath the Sverdrup Basin lie Paleozoic rocks of the Franklinian Miogeosyncline. The source of the piercement structures is believed to be an evapo-

† Contribution from the Dominion Observatory No. 300. Manuscript received by the Editor May 26, 1969; revised manuscript received October 3, 1969.

* Lockwood Survey Corporation Limited, Toronto, Canada.

‡ Gravity Division, Dominion Observatory, Ottawa, Canada.

No. 300

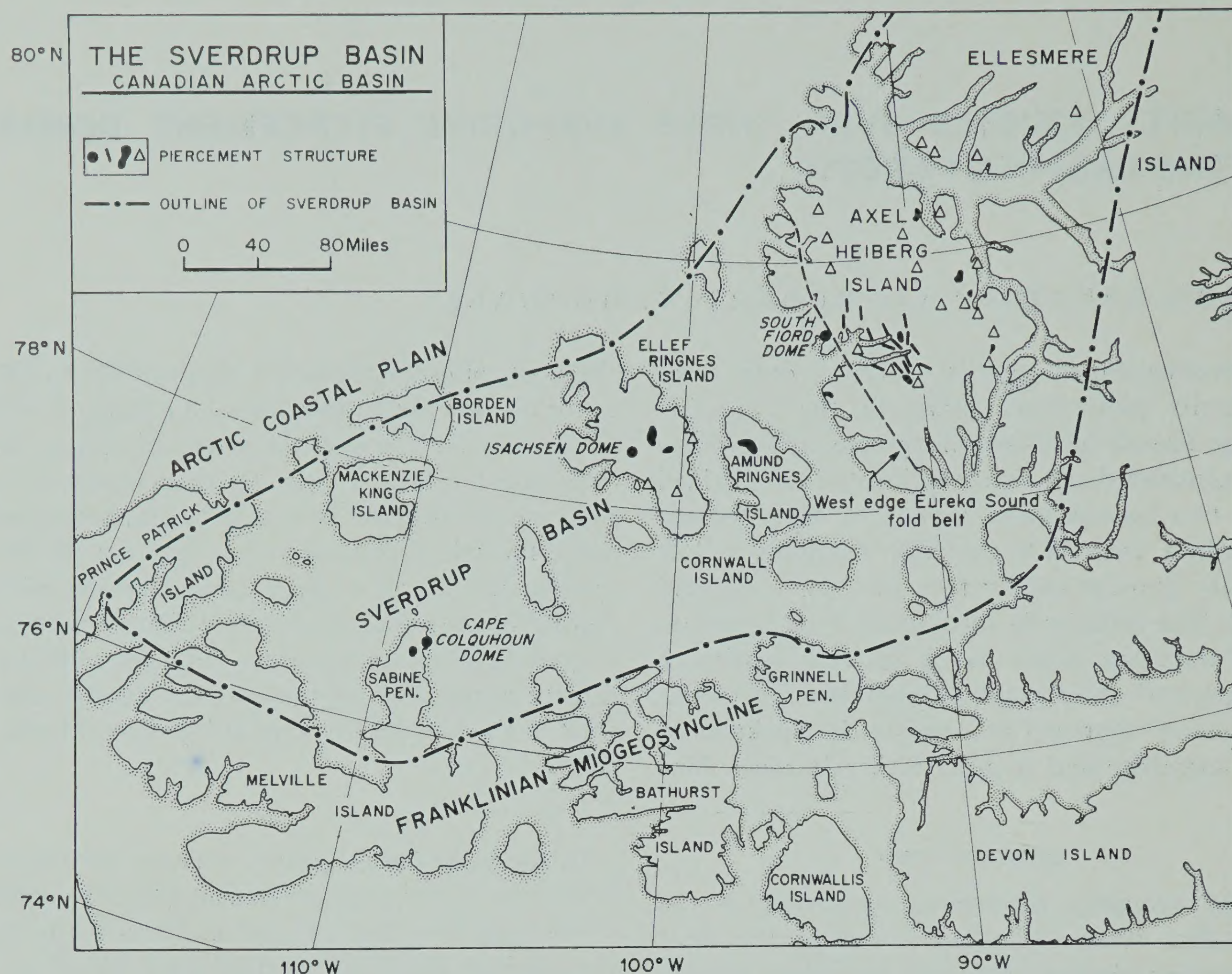

FIG. 1. Location and geological setting of the evaporite piercement structures in the Canadian Arctic (after Gould and DeMille, 1964).

ritic sequence of Carboniferous or Permian age which outcrops along the edge of the basin on Axel Heiberg and Ellesmere Island (Gould and DeMille, 1964).

The dome-shaped diapirs occur west of the Eureka Sound Fold Belt. Gould and DeMille (1964) have attributed their origin to a combination of plastic flow and geostatic loading. On the basis of the preliminary gravity map of Ellef Ringnes Island (Sobczak, 1963), which shows negative anomalies over the domes on this island, they postulate a halite core for the westerly domes. In contrast, Hoen (1964) postulates a gypsum-anhydrite core for the South Fiord Dome, and for most of the diapirs within the Eureka Sound Fold Belt. Within this belt, horizontal compression was probably responsible for the diapiric structures.

The Cape Colquhoun Dome (Figure 2a) is a roughly circular feature covering 36 km² which rises over 200 m above the surrounding plain and is highly dissected by streams. Only brief mentions of the geology of this dome have been made in the published literature. A few gypsum outcrops in the interior of the dome were visited by Tozer and Thorsteinsson (1964) who have described the geology of Melville Island. The dome appears to have intruded a virtually flat-lying Triassic to Upper Cretaceous sequence of sediments at least 3500 m thick. Blocks of limestone and shale of Permian age are present in the dome and probably represent beds which were deposited in the same sequence as the evaporite. Gabbro blocks which are present within this dome may be part of the ring dikes which have been intruded around the outline of the dome (Tozer and Thorsteinsson, 1964). Anhydrite has not been observed on the surface but it may be present beneath the gypsum.

The Isachsen Dome (Figure 3a) is oval in outline and covers about 28 km². The core consists of chaotic blocks of gypsum and anhydrite and is

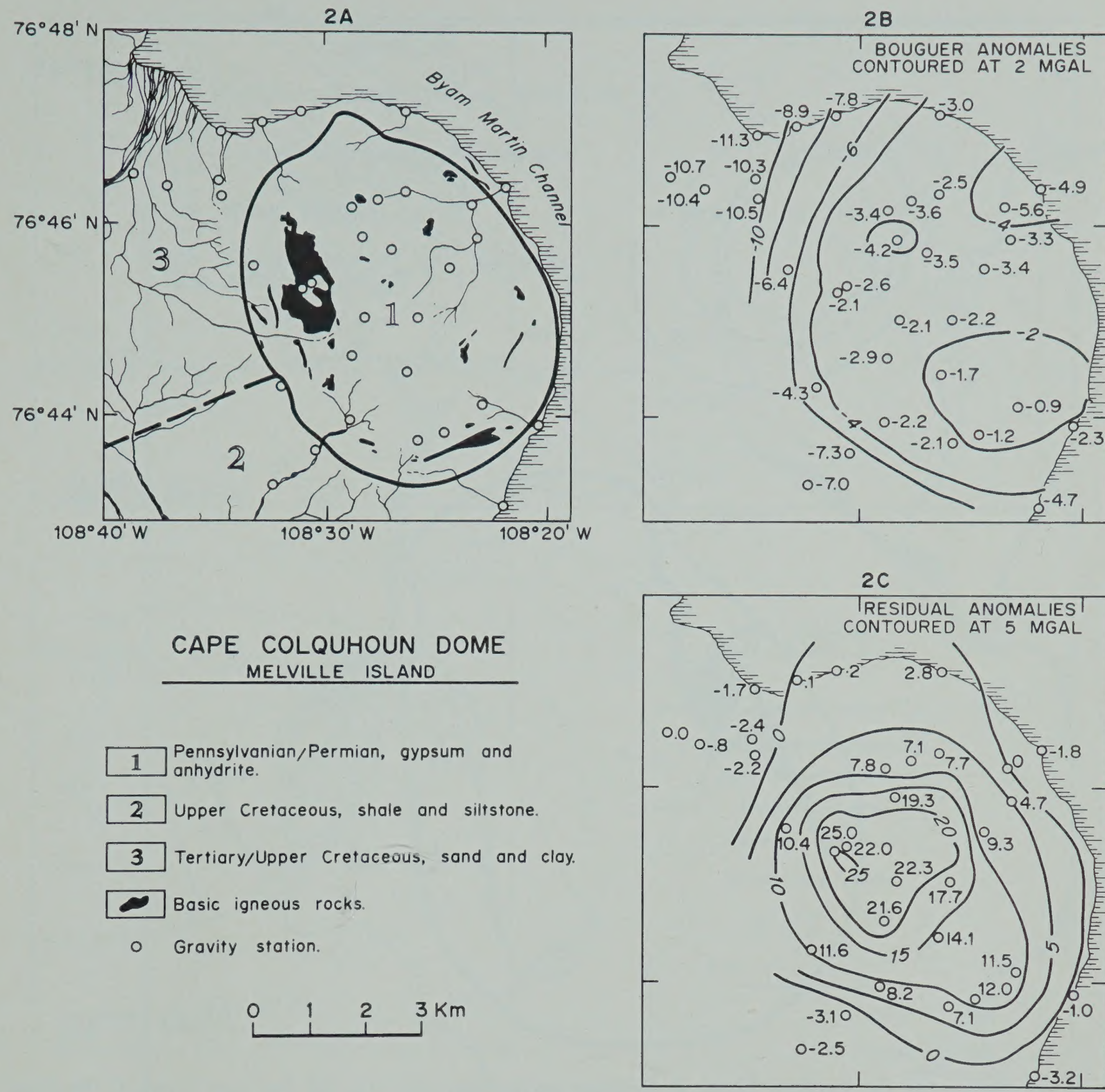

FIG. 2. A. Geology of the Cape Colquhoun Dome. B. Bouguer gravity anomaly over the Cape Colquhoun Dome. C. Residual anomaly due to the mass of the dome over the Cape Colquhoun Dome.

surrounded by a 500 m sheath of anhydrite (Gould and DeMille, 1964). The dome pierces upturned beds of the Isachsen Formation (sandstone) and Christopher Formation (shales) of Lower Cretaceous age. Heywood (1957) estimates that the dome has moved upward at least 1000 m through these formations. Seismic work by Hobson (1962) and Sander and Overton (1965) suggests that the Permo-Carboniferous source beds of the gypsum and anhydrite lie about 4 km below the surface. Limestone and gabbro blocks have been brought to the surface by the rising action of the gypsum-anhydrite mixture.

The South Fiord Dome (Figure 4a) has been intensively studied by Hoen (1964). The oval dome rises 400 m above the surrounding terrain and covers 31 km². As in the Isachsen Dome, adjacent strata thin and dip away from the near-vertical sides of the dome suggesting that in its final stages the dome grew, in part, contemporaneously with sedimentation. From measured thicknesses of outcropping formations it is estimated that the dome is surrounded by 4000 to 6000 m of Triassic to Lower Cretaceous sediments. The exposed anhydrite cap consists of 400 m of layered anhydrite and limestone. Dike-like gabbro masses

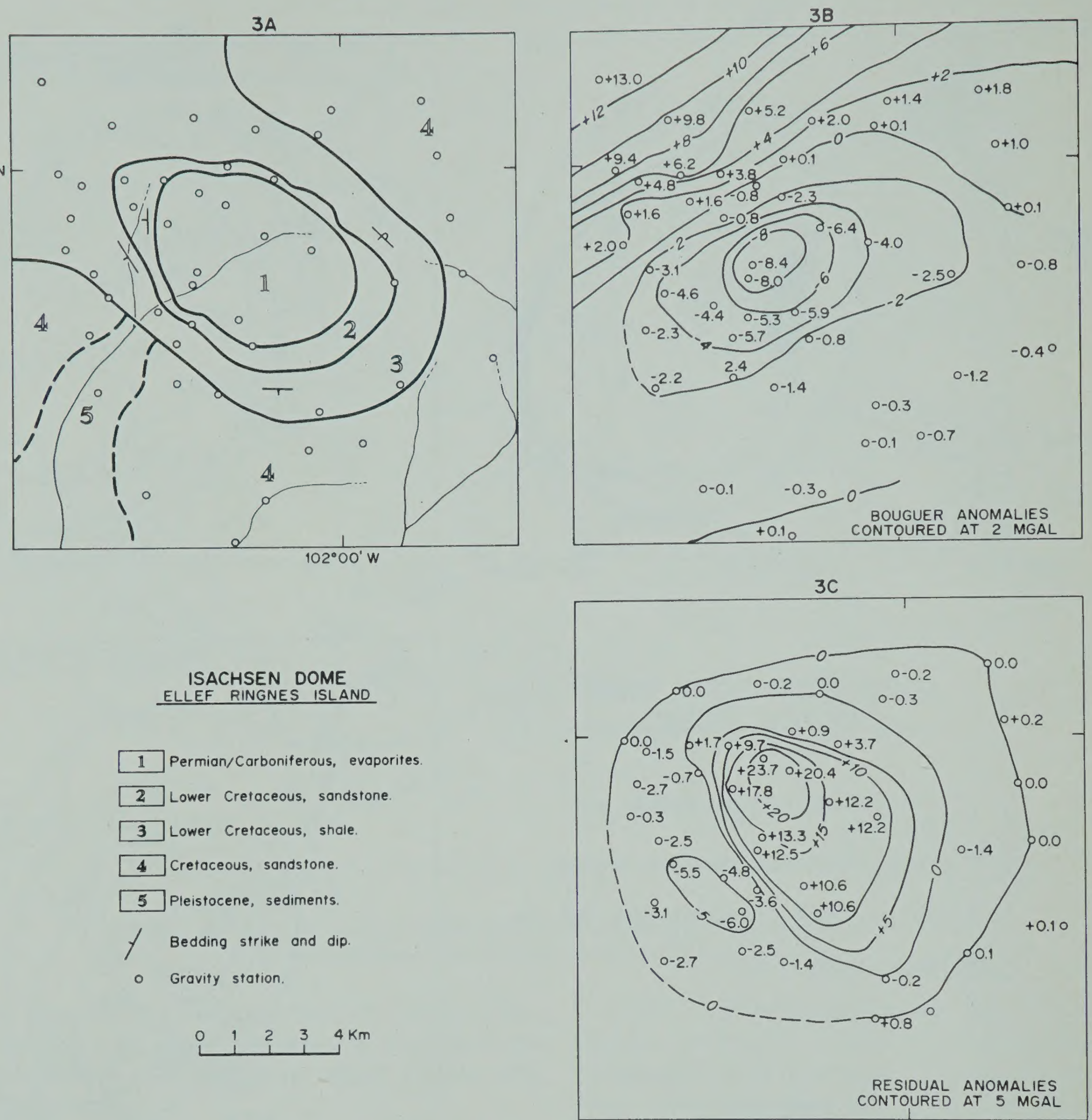

FIG. 3. A. Geology of the Isachsen Dome. B. Bouguer gravity anomaly over the Isachsen Dome. C. Residual anomaly due to the mass of the dome over the Isachsen Dome.

within the dome are interpreted by Hoen (1964) as igneous intrusions which were emplaced after the dome had penetrated the overburden.

GRAVITY SURVEYS

Since 1960, regional gravity surveys have been made in the Arctic Archipelago by the Dominion Observatory as part of the Polar Continental Shelf Project. Stations are read at 10 km intervals to map the major features of the gravity field. In 1960, 1961, and 1963 local surveys were made over the three salt domes. Gravity measurements were made using temperature-compensated Worden gravimeters and elevations were measured, simultaneously, with barometric altimeters.

The distribution of gravity stations over the Cape Colquhoun Dome, the Isachsen Dome, and the South Fiord Dome is shown in Figures 2a, 3a, and 4a, while Figures 2b and 3b show the Bouguer anomalies over the domes, contoured at intervals of 2 mgal. The Bouguer anomaly values were calculated with a Bouguer density of 2.40 gm/cm^3. Although the relative gravity values between the stations are known to better than 0.2 mgal, the Bouguer anomaly values have errors of up to 2 to 3 mgal because of errors of up to 5 m in elevation and the absence of terrain corrections. Sample terrain corrections made over the Isachsen Dome

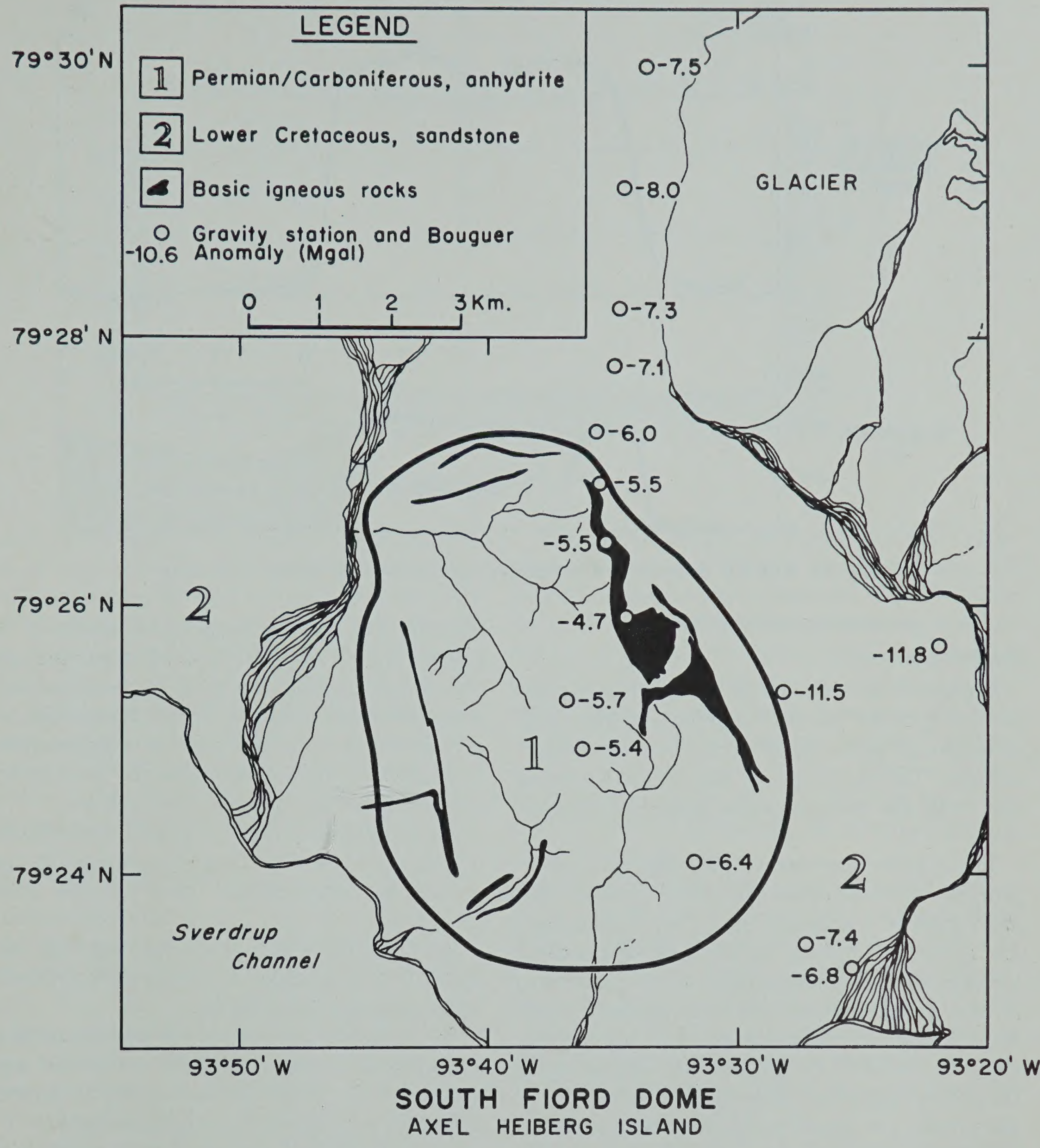

FIG. 4a. Geology and Bouguer anomaly values over the South Fiord Dome.

were of the order of 0.5 to 2 mgal. Similar large terrain corrections can be expected over the South Fiord Dome.

The Bouguer anomaly maps show a high of 5 mgal over the Cape Colquhoun Dome, a negative of 10 mgal over the Isachsen Dome, and a small high of 2 mgal over the South Fiord Dome. The highs could be explained by the presence of the surface anhydrite. but the negative over the Isachsen Dome suggests the presence of gypsum or salt under the anhydrite cap. As the 400 m of anhydrite observed at the South Fiord Dome should itself cause a positive gravity anomaly of 8 mgal—4 times the observed anomaly—there must be a low density layer beneath the South Fiord Dome. Although no negative is observed over the Cape Colquhoun Dome, a low density layer can be assumed beneath this dome too.

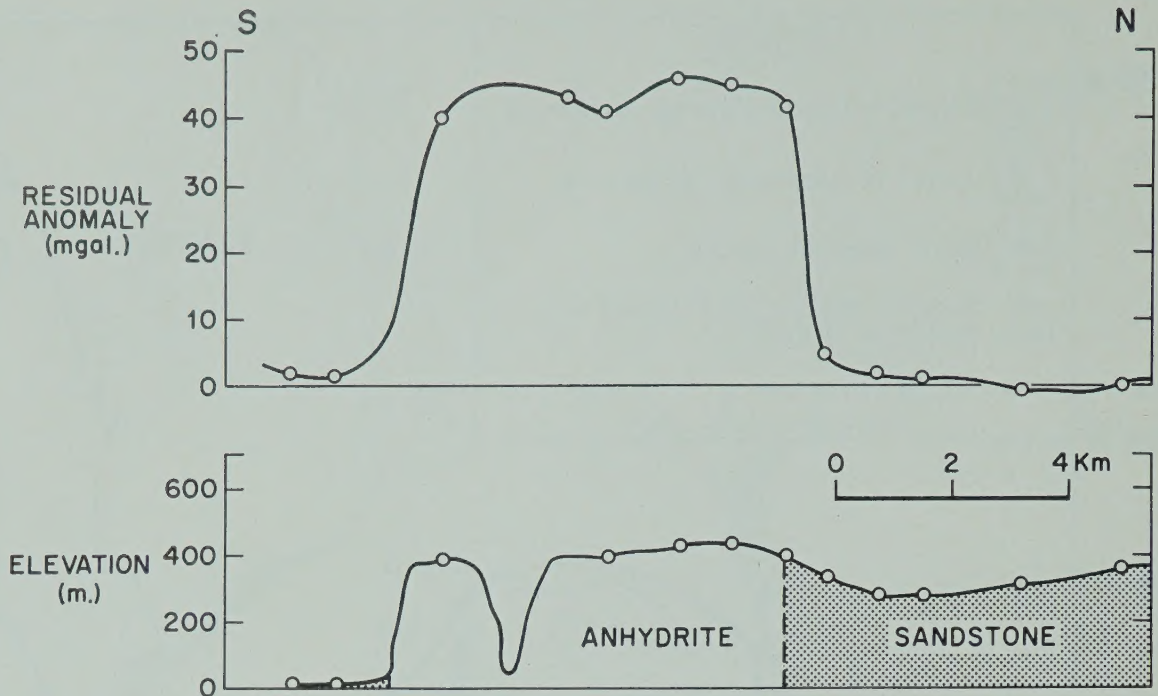

FIG. 4b. Residual anomaly and topographic profile over the South Fiord Dome.

METHOD OF INTERPRETATION

General dome model

A general dome model in the form of a right vertical cylinder has been assumed for the three domes based on the circular nature of the domes' outlines. The simplicity of this model is consistent with the reconnaissance nature of the surveys.

The cylinder has been divided into two homogeneous zones—an upper zone which has a density of 2.9 gm/cm^3 simulating the anhydrite sequence, and an underlying low density zone representing the sequence of gypsum/halite which is assumed to have an effective density of 2.3 gm/cm^3. If salt alone is beneath the anhydrite cap, this density should be closer to 2.2 gm/cm^3, but because of the lack of conclusive evidence for the salt and also the presence of denser rocks (limestone and gabbro) in the dome cores the value 2.3 gm/cm^3 is a fair approximation. The densities of the sediments surrounding the domes have been analyzed by Sobczak (1963) and by Sobczak et al (in preparation). They give a range of densities of 2.32 gm/cm^3 to 2.48 gm/cm^3 for Sverdrup Basin rocks on the basis of seismic velocities, surface sample densities, and density profiles. For this study, a value of 2.40 gm/cm^3 has been chosen.

The addition of a third zone in which a gradation in density occurs between the upper and lower zones would perhaps make the model more realistic, but the reconnaissance nature of the gravity survey and the lack of subsurface geological information hampers the solution of a three-parameter problem. The solution of the two-parameter problem will yield a minimum estimate of the dome's extent beneath the anhydrite zone, if in fact the transition zone exists.

Three cylinders, each of radius a of differing density contrast, must then be considered in computing the gravitational effect of the model (Figure 5).

(a) Cylinder 1 simulates the exposed dome which rises to a height H_1 above the surrounding terrain and has a density D_1.

(b) Cylinder 2 represents the buried part of the anhydrite zone to a depth H_2 below the upper surface of the dome and has a density contrast D_2 relative to the surrounding sediments.

(c) Cylinder 3 is the low density region forming the remainder of the dome to a depth H_3 below the dome's upper surface and has a density contrast D_3 relative to the surrounding sediments.

Gravitational effect of a right circular cylinder

Nabighian (1962) has developed a formula for the attraction of a right vertical cylinder. The expression may be written in closed form involving the sum of the complete elliptic integrals of the first and second kinds and Heuman's Lambda function. Nagy (1965) has adapted Nabighian's

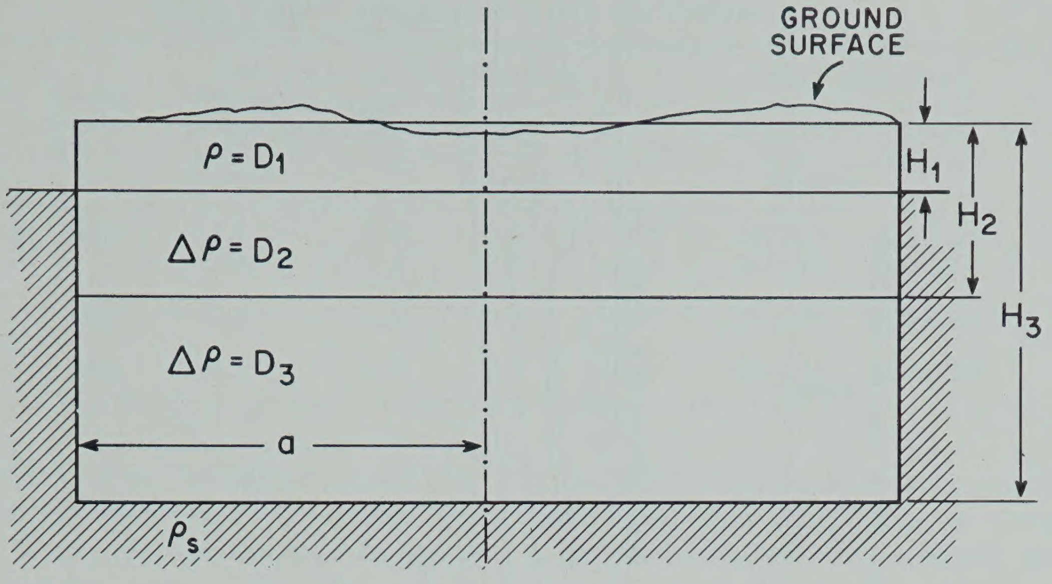

FIG. 5. General dome model.

equations for digital computation by developing each of the three functions in power series. His computational method was successfully tested by both checking his estimates of the values of the three functions against published values and comparison of his results with the gravitational effect of a cylinder composed of 150 right-rectangular prisms. On the basis of this test, Nagy's adapted version of Nabighian's expression was incorporated in a computer program to carry out the computations involved in the gravity interpretation.

Data reduction and analysis

The gravity surveys were done over rather unusual topography. Gravity stations on the domes were often 300 m above stations surrounding the domes. This, and also the difference in bedrock densities underlying on-dome and off-dome stations, led to the adoption of a rather special approach to gravity data reduction.

Bouguer gravity was calculated at each of the "off-dome" stations, assuming a bedrock density of 2.4 gm/cm^3. The terrain effect of the dome in each case was not calculated at this point.

Free air gravity was calculated at each of the "on-dome" stations. Because of the deep dissection of internal parts of the domes by stream erosion, terrain correction was estimated and applied to these data, using topographic information from field traverse notes. The advantage in the use of free air reduction for on-dome stations is that no assumption concerning density variation with depth is necessary.

The regional field in the vicinity of Cape Colquhoun and Isachsen Domes was then estimated from the gravity maps of Sobczak et al (1964). In the case of South Fiord Dome where this coverage was not available, the regional field was assumed to be that defined at the stations furthest from the dome. These regional trends were removed from the above reduced data and the "residual" gravity g_i was contoured for each dome (Figures 2c, 3c, and profile in Figure 4b). The residual g_i was assumed to reflect exclusively the observed gravity effect of each dome.

A "residual" of +45 mgal compares with a Bouguer anomaly of 2 mgal over the South Fiord Dome (Figures 4a and 4b). A 400 m-thick slab of anhydrite with density 2.9 gm/cm^3, would produce a 45 mgal anomaly. In the case of the Isachsen Dome the +24 mgal residual corresponds to an anhydrite slab thickness of about 220 m. Elevations of stations on this dome range from 180 to 200 m above sea level.

After g_i was determined, the root-mean-square deviation between the computed gravity effect g_{oi} and the observed dome effect g_i is computed for different values of the parameters H_2 and H_3 (D_1, D_2, D_3, and H_1 assigned). A surface may then be contoured in parameter space from the computed points (Figure 6):

$$\delta(H_2, H_3) = \sqrt{\sum_{i=1}^{n} (g_{oi} - g_i)^2/n}.$$

The interpretation of these two parameters is

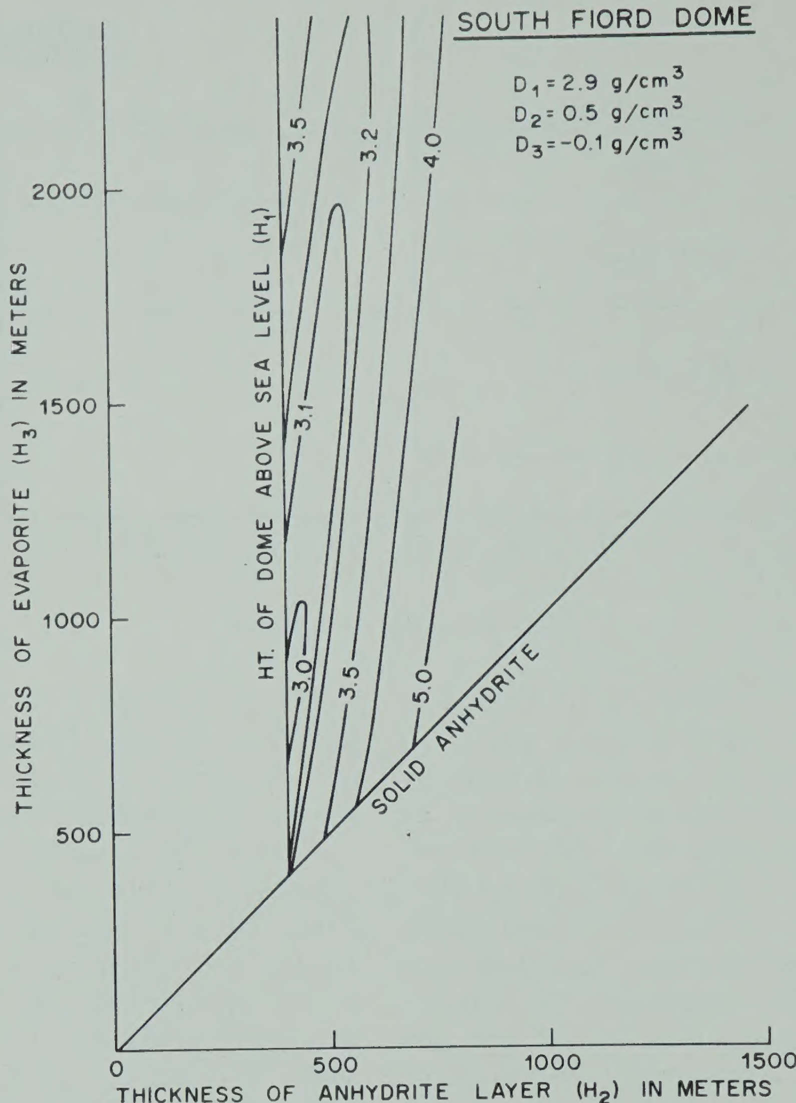

FIG. 6. Deviation surface for the South Fiord Dome. Values on the contours represent the value δ, the root-mean-square deviation between the computed gravity effect and the residual anomaly.

made by finding the position of the minimum of the surface $\delta(H_2, H_3)$.

An important criterion for choosing a particular density zoning is the condition that the value of the minimum must be comparable to the accuracy of the survey data.

Computation of the δ-surface is restricted to the sector of parameter space between the two lines $H_2=H_1$ and $H_2=H_3$. The line $H_1=H_2$ serves as a lower limit based on the observation that the anhydrite zone extends at least to sea level in the dome studied (exception, the Cape Colquhoun Dome where its presence and minimum extent is assumed). The line $H_2=H_3$ is an upper limit because along this line the dome consists entirely of high density anhydrite and the low density zone ceases to exist.

RESULTS

The results of the depth calculations are shown in Table I for the density contrasts used. An example of the surface generated by the technique for the South Fiord Dome is shown in Figure 6. The minimum of the surface is described by an elongated trough which is subparallel to the H_3 axis. This is due to the high sensitivity of the method to variations in the thickness of the near-surface high-density anhydrite zone compared to variations in thickness of the deeper evaporite zones with the low density contrast.

The results for the Cape Colquhoun Dome, if an anhydrite layer is assumed at the surface, gave a maximum depth of 1500 m for this dome. As this appeared unreasonable, a second model was tried in which the density contrast $D_1=2.6$ gm/cm^3 (i.e., the top layer was not pure anhydrite but a mixture of gypsum and anhydrite) was assigned. This model gave a maximum depth of 2800 m—still a very shallow value.

The Isachsen Dome extends to a depth of be-

Table 1. Summary of depth calculations

	Radius of cylinders (a) m	Density of sediments gm/cm³	Density contrasts D_1 gm/cm³	D_2	D_3	Range of thickness: Anhydrite zone m	Total thickness m	Root mean sq. deviation mgal
Cape Colquhoun	3000	2.4	2.9	0.5	−0.1	200–300	500–1500	2.0
		2.4	2.6	0.2	−0.1	300–500	700–2800	1.9
Isachsen	2750	2.4	2.9	0.5	−0.1	250–300	3500–4500	3.2
South Fiord	3600	2.4	2.9	0.5	−0.1	400–550	800–2000	3.0

tween 3500 and 5500 m. The deeper depth is in fair agreement with the seismic information. The higher value of the root-mean-square deviation (3.2 mgal) probably reflects the more rugged topography of the dome and the presence of substantial blocks of limestone and gabbro. The gravity effect of the Isachsen Dome (Figure 3c) is the only one of the three observed dome-effect maps which shows a sombrero-like pattern, i.e., a gravity low around the gravity high which is due to the anhydrite—a situation that is commonly encountered in other salt dome provinces.

A range of depths of 800 m to 2000 m has been calculated for the South Fiord Dome. The low maximum value for this dome suggests that the source of this anomaly is a buried anticline—perhaps an extension at depth of the Eureka Sound Fold Belt (Figure 1).

The thickness of the anhydrite zones at the Isachsen and the South Fiord Domes is only a little greater than the surface expression of these domes.

It must be emphasized that these depth estimates are minimum if any or all of the following features are involved:

(a) the existence of a transition zone in which a gradation occurs between the low density (gypsum/rock salt) and high density (anhydrite) zone;

(b) the cross-sectional area of the dome decreases with depth, i.e., it has a tear-shaped cross section;

(c) the density contrast of the low-density region is less in magnitude than 0.1 gm/cm³ with respect to the surrounding medium.

The interpretations with regard to total dome extent really depend, to a large extent, on the rather simplified assumption of dome shape. When additional gravity data are secured, as well as accurate topographic maps, it is strongly recommended that further evaluation, using a more geologically reasonable model to simulate the observed data, be done—particularly if additional geological control can be incorporated.

REFERENCES

Gregory, A. F., Bower, M. E., and Morley, L. W., 1961, Geological interpretation of aerial magnetic and radiometric profiles, Arctic Archipelago, Northwest Territories: Geol. Surv. Can., Bull. 73.

Gould, D. B., and DeMille, G., 1964, Piercement structures in the Arctic Islands: Bull. Can. Petrol. Geol., v. 12, p. 719–753.

Heywood, W. W., 1957, Isachsen area, Ellef Ringnes Island, District of Franklin: Geol. Surv. Can., Paper 56-8.

Hobson, G. D., 1962, Seismic exploration in the Canadian Arctic Islands: Geophysics, v. 27, p. 253–273.

Hoen, E. W., 1964, The anhydrite diapirs of central western Axel Heiberg Island: Axel Heiberg Research Reports (McGill University), Geology, No. 2.

Nabighian, M. N., 1962, The gravitational attraction of a right vertical cylinder at points external to it: Geofisica Pura E Applicata, v. 53, p. 45–51.

Nagy, D., 1965, The evaluation of Heuman's Lambda function and its application to calculate the gravitational effect of a right circular cylinder: Pure and Applied Geophys., v. 62, p. 5–12.

Sander, G. W., and Overton, A., 1965, Deep seismic refraction investigation in the Canadian Arctic Archipelago: Geophysics, v. 30, p. 87–96.

Sobczak, L. W., 1963, Regional gravity survey of the Sverdrup Islands and vicinity: Gravity Map Series No. 11, Dom. Obs., Ottawa, Canada.

——— Weber, J. R., Goodacre, A. K., and Bisson, J. L., 1964, Preliminary results of gravity surveys in the Queen Elizabeth Islands: Gravity Map Series Nos. 12–15, Dom. Obs., Ottawa, Canada.

——— Weber, J. R., and Roots, E. F., 1970, Geophysical investigations over the Queen Elizabeth Islands: in preparation.

Tozer, E. T., and Thorsteinsson, R., 1964, Western Queen Elizabeth Islands, Arctic Archipelago: Geol. Surv. Can., Mem. 332.